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Abstract. The *VISLAN* system is based on one of the newest developments in optical localiser tracking, where the localiser reflects light shone on it (passive illumination) rather than emitting light. In experiments with a CT-compatible skull phantom we evaluated the *VISLAN* system in comparison with a widely used stereotactic system, the Cosman-Roberts-Wells frame (Radionics Inc). The mean Euclidean difference in localising points initially defined in CT images was 2.5mm across a wide range of target positions. We estimated the accuracy of the *VISLAN* system with the same phantom set up but independently of the stereotactic frame, and showed a mean Euclidean error of 1.0mm. We concluded that the majority of the discrepancy between the two systems was accounted for by the inaccuracy of the CRW frame. It would be inappropriate to regard the frame based systems as a satisfactory gold standard for estimating the accuracy of *VISLAN*. However, frame-based and frameless guidance may be needed in the same operation, and it is important for such systems to be compared.

Keywords surgical guidance; optical localiser; stereo video; stereotactic surgery; phantom; evaluation; neurosurgery.

1 Introduction

Several new surgical guidance systems have recently been developed which are based on optical tracking of a hand-held localiser (e.g. Adams et al, 1990; Bucholz & Smith, 1993; Buurman & Gerritsen, 1996). Most of these localisers carry small light-emitting diodes (LED's) arranged on the handle. A cable connection is required to power the LED's and to control the timing of their illumination pulses so as to avoid ambiguities during the detection and tracking processes. The newest development in optical tracking is to use passive illumination: in other words, the localiser merely reflects light shone on it, rather than emitting light. The *VISLAN* system (Colchester et al, 1994a; Colchester et al, 1996) is based on this principle. A distinctive pattern on the localiser handle is detected and tracked automatically in stereo video images acquired through a pair of video cameras. The localiser is freed from any connecting cables, which increases convenience for the surgeon and simplifies construction.

Surface-based registration is used routinely in several localiser based systems and enables them to be used without a stereotactic frame. Usually, the localiser is drawn over the surface of the scalp, tracing numerous surface points, which collectively form a sparse model of the scalp surface. This model is matched to a well-sampled scalp model derived from pre-operative MR or CT. As long as the surface points acquired intra-operatively provide enough geometric information to allow an unambiguous match to be computed, this is a satisfactory non-invasive method for pre-to intra-operative registration. Tracing can be carried out through the patient's hair and is not restricted to shaved areas. Where sufficient stable features are visible, for example by inclusion of eyebrows, passive illumination systems can offer highly effective alternatives to tracing. With the *VISLAN* system, the surface visible to the video cameras is briefly illuminated with a striped light pattern, and a well-sampled 3-D surface patch is reconstructed from the stereo video images (Colchester et al, 1994b; Henri et al, 1995).

It is still believed by many neurosurgeons that the conventional stereotactic frame (SF) offers the highest localisation accuracy of available guidance systems, but accumulating data shows that this is no longer necessarily true (Bucholz & Smith, 1993; Maciunas et al, 1994). In fact, what the SF systems offer is a clinically well validated and consistent, if invasive, method of registration, as well as mechanical control of a needle for biopsy, recording or ablation. The scales on most systems which are adjusted on the frame when the needle is positioned with the SF are only graduated in millimetres and accuracy can in principle be surpassed by many newer frameless systems. Well designed point markers implanted into the skull pre-operatively can match the SF in consistency and exceed its accuracy (Maciunas et al, 1993) but this approach still requires minor surgery, prior to imaging and the main operation. Surface-based registration probably requires more skilful interaction and judgement than stereotactic frame registration, so it is probably harder to ensure consistency in routine use, but accuracy with this approach can probably also match or surpass SF accuracy when good surface measurements are obtained.

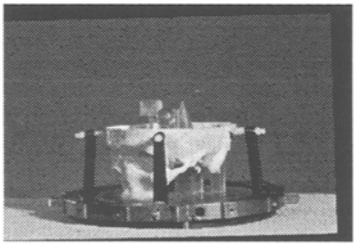
Because SF systems are a de facto standard, newer systems need to be compared with them. Comparative evaluation should not only be competitive in establishing which system is "better" than the other in a particular aspect. It is also necessary to evaluate the possibilities of using two systems during the same surgical procedure. Thus, in certain operations, a SF may be required for directing and holding a needle, and at the same time freely mobile, hand held localiser with no attachments could be very useful.

We therefore undertook experiments to compare a) localisation using a well-known stereotactic frame system, with b) localisation using the *VISLAN* system in a phantom.

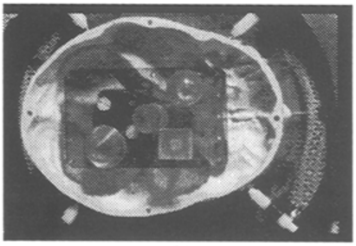
2 Methods

Phantom (Fig 1) A CT compatible skull phantom was used for these experiments. The CRW stereotactic base ring was attached to it by the standard skull pins. A cubic and a conical object were fixed firmly to its interior, and the apices of these were used as point landmarks which could be identified in the CT images and physically accessed by both systems.

VISLAN System The *VISLAN* pre-operative visualisation and planning software (Zhao & Colchester, 1994) was run on an HP-735 workstation. Facilities for simultaneous viewing of orthogonal slices through the CT of the phantom were used for interactive localisation of point landmarks in CT co-ordinates. The surface of the skull phantom was segmented and stored as a 3-D list of (contiguous) voxels. The intra-operative system consisted of the following parts. A pair of video cameras were mounted 1m apart and positioned about 1.2m above the phantom. (Fig 2(a)). For processing of the video data, the computer outputs were digitised and transferred to a Sun SPARC processor, in turn connected to the HP graphics workstation. The camera pair was calibrated by processing the stereo images of an accurately machined tile on which a matrix of dots was etched. The localiser, carrying on its handle the characteristic *VISLAN* pattern, (Fig 2(b)) was modified from a standard pointed-tip design. A basic model of the pattern was stored in the computer allowing real time tracking. The modification consisted of a conical dimple with shallow bevel drilled into the upper surface of the shaft (about 10 mm from the tip). This allowed positive engagement with any pointed object such as the CRW pointer or the apex of the conical object in the phantom. The localiser was calibrated by docking the dimple on a fixed spike and moving it through as wide a range of orientations as possible; this was repeated at several different positions in the camera field of view. The detected positions and orientation of the handle were then analysed to generate a new model of the complete localiser, providing a revised offset for the apex of the concave dimple, replacing the normal offset used for the pointed tip. For the *VISLAN* surface-based registration, a projector shone a pattern of alternating light and dark bars onto the surface of the phantom and the stereo images were processed to reconstruct the surface geometry in 3-D. Although the plastic phantom surface imitated a skull, the geometry of the surface patch analysed closely resembled the geometry of the scalp and this gave a good approximation to in vivo performance when this *VISLAN* registration option is used. To compute the pre- to intra-operative registration, a chamfer volume was created from the CT surface reconstruction and the position and orientation of the video surface reconstruction was then modified until the distance between the two was minimised (Henri et al, 1995). A more detailed description of the operation of the *VISLAN* system is available in Colchester et al, 1996.



(a)



(b)

Fig. 1 (a) and (b) CT-compatible skull phantom. The skull vault is removed showing the objects inside.

Stereotactic frame For Experiment 3, a Cosman-Roberts-Wells (CRW) stereotactic frame (Radionics Inc.) was used. The base ring of the CRW frame was attached to the phantom by means of standard bone screws. For pre-operative calibration, a frame containing radio opaque rods (the N-fiducials) was attached to the base ring around the outside of the skull phantom (Fig 3(a)). The sections of rods were visible on the CT slices, as discs where a rod was roughly perpendicular to the plane of the slice and as ovoid features where a rod was oblique (Fig 3(b)) For one CT slice, the centres of these rod images were marked interactively with a cursor and the CT co-ordinates noted and typed into the calculator provided with the CRW frame which computed registration for that CT slice. Target points on the slice were chosen interactively, their

CT co-ordinates noted, and their frame co-ordinates computed on the calculator. For "intra-operative" use of the CRW system, the calibration frame was removed from the base ring and replaced with the adjustable pointer holder (the operating arc) (Fig 3(c)). A rigid 160 mm pointer was locked in the block and the scales of the holder were then adjusted according to the output of the calculator, so that the pointer tip ended in the predicted physical position, in relation to the phantom, of the target point that had been chosen in the CT.

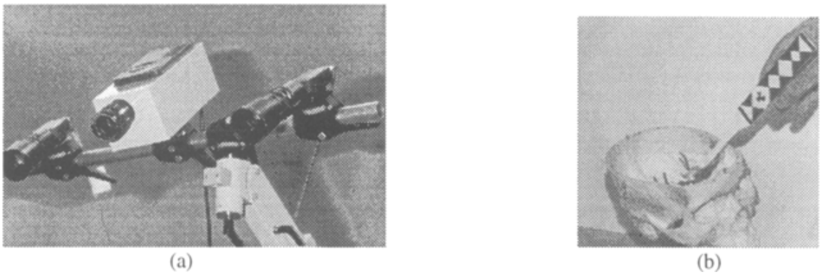


Fig. 2 The VISLAN System: (a) Close-up view of video-cameras mounted on a cross-bar. The projector in the centre generates a pattern of stripes on the head during stereo surface patch reconstruction. (b) The VISLAN localiser showing the diamond pattern used with passive illumination for real-time video tracking.

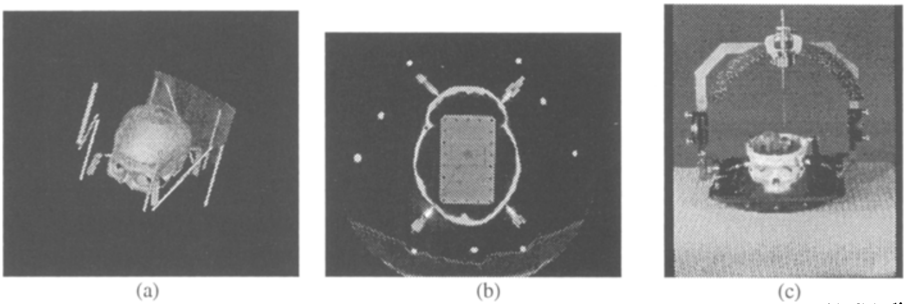


Fig. 3 (a) 3-D reconstruction from a CT scan of the skull phantom showing the calibration rods. (b) CT slice showing the appearances of the calibration rods. (c) Phantom with stereotactic frame attached showing the 'intraoperative' arrangement with the pointer held in a block on the operating arc.

3 Results

3.1 Experiment 1: Repeatability of *VISLAN* Localiser Readings

At each of eight different positions spaced widely throughout the simulated "operative" field, VISLAN localiser readings were recorded with the localiser held in three different orientations while docked onto the SF pointer. As far as possible, the point of the landmark was kept in good engagement with the localiser dimple in all orientations, although there must have been small deviations in position measurement due to mechanical variation in this engagement, as well as optical and computational considerations in localiser tracking. The positions were transformed into CT co-ordinates for purposes of comparison with experiments 2 and 3. The same transformation was used for all readings and did not affect the magnitude of the variability: Thus, this experiment did not test registration accuracy. The stereotaxic frame (SF) pointer was used as a convenient adjustable docking point but in principle any rigid spike could have been used and the *VISLAN* readings were not compared with the SF readings in this experiment. Table 1 shows the maximum and root mean square (rms) differences in *VISLAN* readings. The rms error was 0.5 mm. The maximum difference in the whole series was 1 mm.

Target Position	MAX DIFFERENCES				RMS DIFFERENCES			
No.	x	y	z	Euclid. Diff.	x	y	z	Euclid. Diff.
1	0.55	0.51	0.57	0.95	0.13	0.12	0.13	0.16
2	0.29	0.53	0.24	0.53	0.08	0.13	0.07	0.16
3	0.49	0.32	0.20	0.57	0.13	0.08	0.05	0.26
4	0.89	0.79	0.31	1.02	0.21	0.19	0.07	0.39
5	0.33	0.58	0.23	0.69	0.08	0.16	0.06	0.55
6	0.52	0.29	0.40	0.60	0.13	0.08	0.10	0.60
7	0.22	0.49	0.14	0.53	0.06	0.12	0.04	0.63
8	0.21	0.20	0.15	0.27	0.05	0.05	0.04	0.63
Overall average	**0.44**	**0.46**	**0.28**	**0.65**	**0.09**	**0.10**	**0.07**	**0.48**

Table. 1 Repeatability of VISLAN localiser readings.

3.2 Experiment 2: Accuracy of *VISLAN* in Localising Landmarks defined in CT Co-ordinates

Eight point landmarks were chosen as being clearly identifiable by eye in the CT images and physically accessible to the *VISLAN* localiser in the phantom with the frame in place. These were seven of the eight corners of the cubic object in the phantom, and the tip of the conical object. In Table 2, the cube corners are identified as being anterior or posterior (A or P), left or right (L or R), and top or bottom (T or B). In the CT image, the experimenter viewed orthogonal cuts through the CT data, using the *VISLAN* pre-operative software package, and positioned the cursor as accurately as could be judged on the point landmarks. The cursor could be positioned with sub-voxel accuracy, because after zooming (this used tri-linear interpolation), screen pixels were smaller than CT voxels . Therefore, the landmarks were localised by eye to within a fraction of a CT voxel size.

The *VISLAN* localiser was tracked in the usual way by the video system. The intra-operative co-ordinates of its position were transformed into CT co-ordinates using the *VISLAN* surface-based registration matrix which was derived by using patterned light surface reconstruction.

These two independent estimates of the POPR co-ordinates were compared (Table 2) and are a measure of the *VISLAN* localisation accuracy, compared against the co-ordinates from visual identification of landmarks in the CT images. Note that this experiment does not use the SF registration but independently assesses *VISLAN* accuracy in the context of the SF frame use. Table 2 shows the errors in the *VISLAN* - predicted location of the landmarks in the CT images. The scalar differences are the correct accuracy measure (ignoring the positive or negative signs). The mean Euclidean error was 1.0 mm, and maximum error 1.8 mm.

Landmark	**Error (Visual-*VISLAN*)**			
Description (see text)	x	y	z	**Euclid. Diff.**
Cone Tip	0.74	0.91	-0.49	1.27
PLB Cube	-0.64	-0.70	0.11	0.95
PRB Cube	-1.07	-0.63	0.16	1.25
ARB Cube	-1.53	0.96	0.37	1.85
ALB Cube	0.29	-0.17	0.46	0.57
PRT Cube	-0.23	-0.19	0.89	0.94
PLT Cube	-0.80	-0.10	-0.05	0.81
ALT Cube	0.23	0.06	0.26	0.35
Bias(true mean)	-0.38	0.02	0.21	
Accuracy (mean scalar value)	0.69	0.47	0.35	1.00

Table 2 Accuracy of VISLAN localisation..

3.3 Experiment 3: Comparison of Localisation by Frame-based Stereotaxy with the *VISLAN* System

In experiment 3, the normal procedure for SF localisation was followed. Well-spaced targets were identified in the CT images and were chosen so as to be accessible to both the stereotactic needle and the *VISLAN* localiser. The SF calibration was carried out for each chosen CT slice by identification of the SF fiducial rods within the slice. The CT co-ordinates of the fiducials were then manually entered into the CRW programmable calculator, which matched these co-ordinates to a stored 3-D model of the rods, and derived the SF calibration matrix for that slice. The target co-ordinates were then transformed into SF co-ordinates by the calculator, which listed the sliding scale settings which needed to be set for the frame. These adjustments were then made on the frame, supposedly leaving the SF needle tip in the position relative to the physical phantom that had been specified on the CT images.

For the *VISLAN* system, surface based registration was used. The skull surface was first segmented from the CT data. Then, a portion of the skull surface visible to the cameras was illuminated with the striped light and stereo reconstruction of the surface carried out. These two surfaces were then matched and the CT - to - *VISLAN* intraoperative registration established. The *VISLAN* localiser was then tracked by the cameras, having been previously calibrated for the dimple as opposed to the point, and the positions transformed into CT co-ordinates. The localiser dimple was then docked onto the SF needle. Three "instantaneous" localiser positions were averaged to reflect the fact that the surgeon would obtain several readings with the localiser if the position of a target or landmark was particularly important.

In this experiment, the normal procedure for SF localisation was followed. Well-spaced targets were identified in the CT images and were chosen so as to be accessible to both the stereotactic needle and the VISLAN localiser. The SF calibration was carried out for each chosen CT slice by identification of the SF. Then, the two sources of the CT co-ordinates could be compared: one source was the initial (locally arbitrary) choice of the target position by the user; the other was the *VISLAN* localisation of the SF needle, projected back into the CT data. This comparison was repeated for ten target positions, selected to cover as wide a field of view as possible around the phantom.

Table 3 shows the differences between the SF and *VISLAN* target localisations. The mean Euclidean difference was 2.5mm, and maximum difference was 3.3 mm.

Target No	**Differences in Position, SF to *VISLAN* (mm)**			
	x	**y**	**z**	**Euclid. Diff.**
1	0.28	-1.89	2.73	3.34
2	-1.64	-1.88	0.76	2.61
3	0.95	-0.88	0.32	1.33
4	-0.45	-1.45	0.94	1.79
5	-0.75	-2.54	1.19	2.90
6	-0.06	-2.21	1.80	2.85
7	-0.34	-2.33	1.44	2.76
8	-0.92	-1.66	1.29	2.29
Bias (true mean)	-0.46	-1.86	1.31	
Mean Scalar Difference	0.71	1.86	1.31	**2.48**

Table 3 Differences between Stereotactic Frame and VISLAN localisation target.

4 Discussion

The present experiments confirm the reproducibility of *VISLAN* localisation (Expt 1) and its accuracy (Expt 2). We previously reported a phantom-based method for evaluating overall system accuracy (Holton-Tainter et al, 1995) but in those experiments we used specially designed markers to allow accurate sub pixel localisation of point targets to be computed in tomographic images; the mean localisation error was found to be 0.8 mm. In contrast, Experiment 2 in the present paper uses visual estimation of positions in the CT scans (as is normally employed in the use of stereotactic frames) but our pre-operative viewing and planning software did allow subvoxel target positions to be estimated interactively. In this context, the mean localisation error was 1.0mm.

Experiment 3 directly compared stereotactic frame localisation with *VISLAN* localisation. The target for the SF was chosen arbitrarily in the CT images and the SF needle set up carefully in what would have been the exact physical position of the target, if the SF was perfectly accurate. In principle, we could then have started with the same CT location, moved the *VISLAN* localiser to the exact physical position specified by *VISLAN*, clamped the *VISLAN* localiser, and measured the physical distance between the *VISLAN* localiser and the SF needle tip. However, this would have been difficult to carry out in practice and would have introduced additional sources of experimental error. We therefore took the SF needle position as a fixed starting position for the *VISLAN* localiser, mapped the localiser intra-operative co-ordinates back to the CT using the *VISLAN* registration matrix, and were then able to compare numerically these CT co-ordinates with the initial, arbitrarily chosen co-ordinates. The results show that the SF and the *VISLAN* localisations have a mean discrepancy of 2.5mm across a wide range of the potential positions of targets. Given the accuracy of the *VISLAN* localisation shown independently of the SF in Experiment 2, the biggest contribution to the discrepancy must come from the inaccuracy of the SF system rather than the *VISLAN*, and it would therefore be inappropriate to regard the SF as a satisfactory gold standard for accuracy measurements.

With regard to the possibility of using both systems during the same surgical procedure, this degree of agreement between the two systems would be satisfactory for most neurosurgical requirements, for example for an operation which required accurate needle positioning but also needed a wider craniotomy and navigational assistance with a hand-held localiser. Another scenario to consider is the use of a *VISLAN* localiser in a clamp system, to control a needle directly. It is planned to upgrade the tracking software so that more than one localiser can be tracked simultaneously, and this would allow the concurrent use of a *VISLAN* guided clamped needle assembly as well as a freely moveable hand-held localiser.

Phantom studies of the kind presented here are a necessary part of the evaluation of a guidance system but such results generally only provide a guide to the best that could possibly be achieved in vivo, when several additional constraints may apply. In particular, it should be remembered that accuracy of any localisation method which depends on pre-operative imaging for defining the surgical target will be limited by any movement of the target, relative to the features used for pre- to intra-operative registration, that may take place during surgery.

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